General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

NASA CR-137878
Report No. R76-912036-17

COST/BENEFIT TRADEOFFS FOR REDUCING THE ENERGY CONSUMPTION OF COMMERICAL AIR TRANSPORTATION

(NASA-CR-137878) COST/BENEFIT TRADE-OFFS FOR REDUCING THE ENERGY CONSUMPTION OF COMMERCIAL AIR TRANSPORTATION (RECAT) Summary Report (United Technologies Research Center) 43 p HC $4.00 CSCL 01C G3/03 N76-28204 Unclas 45906

SUMMARY REPORT

Prepared Under Contract NAS2-8608
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER

JUNE 1976

AUG 1976
RECEIVED
NASA STI FACILITY
INPUT BRANCH

UNITED TECHNOLOGIES RESEARCH CENTER
UNITED TECHNOLOGIES
EAST HARTFORD CONNECTICUT 06108

R08-144-1

NASA CR - 137878
UTRC R76-912036-17

COST/BENEFIT TRADE-OFFS FOR REDUCING THE ENERGY CONSUMPTION OF COMMERCIAL AIR TRANSPORTATION (RECAT)

Summary Report

By F. W. Gobetz and A. A. LeShane

June 1976

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides in the author or organization that prepared it.

Prepared under Contract No. NAS2-8608 by
UNITED TECHNOLOGIES RESEARCH CENTER
East Hartford, Conn.

for

AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

The purpose of the RECAT study has been to provide guidance on the direction future NASA research should take to conserve fuel in the commercial air transport system. To this end, a number of fuel conserving options was defined, none of which represents the likely future evolution of the system, but each of which includes potential elements of a logical future system. Therefore, the predictions of fuel usage, as well as fuel saved relative to the baseline case, should not be employed to draw conclusions regarding the single best direction for research. Rather, the reasons why certain options did or did not result in large estimated fuel savings should be analyzed and understood in order to determine whether a productive direction for research is implied in each case. In the final UTRC RECAT study report (R76-912036-16), an attempt was made to restrict the analysis of results to those areas where clear interpretations can be made and to stress the underlying reasons behind those results. This report is a condensed summary of the final report, comprising major results and an overview of the study conduct.

This study was performed by UTRC under contract to NASA, Ames Research Center. The NASA Technical Monitor was Mr. Louis J. Williams, of the Research Aircraft Projects Office. Associate contractors in the study were the Douglas Aircraft Company, Lockheed-California Company, and United Airlines.

R76-912036-17

Cost/Benefit Trade-offs for Reducing the Energy Consumption of Commercial Air Transportation

(RECAT)

Summary Report

TABLE OF CONTENTS

	Page
ABSTRACT	1
INTRODUCTION	4
Objectives	4
Study Scope	5
Relationship to NASA Programs	8
Approach	9
SIGNIFICANT RESULTS	14
Comparative Measures	14
Comparison of Fuel-Conserving Options	14
Actual and Adjusted Fuel Savings	21
Impacts of Fuel-Conservation Options	23
CONCLUSIONS AND RECOMMENDATIONS	27
Major Conclusions	27
Recommendations	28
DATA SUMMARY	30

R76-912036-17

Cost/Benefit Trade-offs for Reducing the Energy Consumption of Commercial Air Transportation (RECAT)

ABSTRACT

The RECAT study evaluated the opportunities for reducing the energy requirements of the U.S. domestic air passenger transport system through improved operational techniques, modified in-service aircraft, derivatives of current production models, or new aircraft using either current or advanced technology. Each of these fuel-conserving alternatives was investigated individually to test its potential for fuel conservation relative to a hypothetical baseline case in which current, in-production aircraft types are assumed to operate, without modification and with current operational techniques, into the future out to the year 2000. Consequently, while the RECAT results lend insight into the directions in which technology can best be pursued for improved air transport fuel economy, no single option studied in the RECAT program is indicative of a realistic future scenario.

Specific fuel-conserving options examined in the study, in addition to the baseline case, are:

- Operational procedures with and without advanced air traffic control (ATC)
- Retrofit to, or modification of, current aircraft types
- Derivatives of current aircraft types
- New near-term aircraft using current technology
- New far-term aircraft (propfan and turbofan) using advanced technology

Characteristics of each of these options, as they affect either the aircraft themselves or the system in which they operate, were developed by associate contractors in the study effort, and the system effects were analyzed by the United Technologies Research Center (UTRC). Aircraft and operational characteristics were developed by Douglas and Lockheed. These data were then reviewed by United Airlines to insure consistency and realism in the economic and operational parameters characterizing each option, and the data were then transmitted to UTRC for systems analysis.

In the UTRC analysis of the air transport system, the fuel-conserving options were not simply introduced into the future system by mandate; rather, elements of each option were accepted into the system only as they could compete in an economic

sense, thereby promoting realism as to the air transport system which would evolve from each option. The air system simulation involved the generation of the required fleet to meet the forecasted travel demand in each of four forecast years --1980, 1985, 1990, and 2000. The forecasted demand is itself affected by the quality of service offered in each option as measured by fare and trip time; other elements of the demand forecasting process involved a modal split among all competing transportation modes (air, rail, bus, and automobile).

Complete travel statistics for each option -- passenger flow, fuel consumed, air system costs, environmental (noise and emission) impacts. and details of the aircraft fleet -- were computed annually and cumulatively, and were compared with the baseline case and with each other. The fuel conserving potential of each option is thus displayed for purposes of evaluation. In addition, other effects of each option -- demand satisfied, user cost and time, noise and emissions, and required Government spending -- were evaluated in a benefit/cost analysis to add insight into conclusions derived from energy considerations alone. Based on the results generated in the system simulation, impacts of each fuel-conservation option on airlines, the aircraft industry, air travelers, airports, and the Government were quantified, and regulatory implications associated with the possible impacts were discussed. Finally, broad recommendations as to advisable action relating to the fuel-conservation effort are offered.

Of all fuel-conservation measures considered, the strict allocation of fuel to the system, a measure evaluated for the baseline case to test its effect, results in the most dramatic saving of fuel. This approach manifests itself primarily as a forced increase in system load factor, and the magnitude of fuel saving depends on how high load factor can be raised before service is adversely affected. Fuel allocation is. of course, not a conservation measure of the kind to which the study is primarily addressed (i.e., technological fuel-conservation measures), but can be applied, to whatever degree practicable, to any of the technological options studied.

The most effective technological option varies with time. In the very near term, between the base year (1973) and 1978, improvements in operational procedures can save a small amount of fuel but cannot, by themselves, achieve dramatic savings in the long run (though, of course they can be combined with other fuel-conserving measures). However, because of the immediate benefit achievable, and its applicability in other options, it is recommended that the operational procedures options be studied further, particularly as to possible costs of implementation.

Given time to develop aerodynamic and reengining modifications, assumed to be available in 1978, the modification of in-production aircraft results in measurable savings in the interim period between 1978 and 1988.

The early development of new near-term aircraft using present technology would result in a greater fuel saving than any other option in the period between 1988 and 1998. The nearest alternative [illegible]ion would be the development of fuel-conserving derivatives of current aircraft. [illegible] total fuel saved would be somewhat less, the derivative option requires a much l[illegible] fleet investment and could be easier to implement for that reason.

Because new far-term aircraft using advanced technology could not be developed for introduction before 1985, at the earliest, that option does not offer as great a cumulative fuel saving as other options within the study period. However, that option becomes competitive with the new near-term aircraft option in about 199[illegible], and would be clearly superior beyond the year 2000.

A striking result of the study is the developing need in the late 1980's for a large-capacity airplane aimed at good economics and low fuel consumption at short and intermediate stage lengths. The travel growth on high-density routes, many of which are short- to intermediate-range, together with capacity restrictions at hub airports, limit frequency growth, thereby requiring large aircraft.

Although propfan aircraft exhibit superior fuel-economy characteristics to turbofans, the study results did not exhibit a clear fuel saving because of inconsistencies in the input design data. A prime recommendation is that design work be initiated to provide consistent aircraft, both in terms of technology and aircraft size, for subsequent evaluation in the RECAT fleet model.

INTRODUCTION

Since the Arab oil embargo of late-1973 and the consequent energy shortage and subsequent rise in fuel cost, much attention has rightfully been focused on fuel conservation measures in all sectors of the economy. Since transportation consumes some 33 percent of all petroleum fuel, conservation in that sector has been of paramount concern, and even though commercial aviation consumes only about 7 percent of transportation fuel, attention tends to focus on aviation because of its greater energy intensity as compared with other common-carrier modes.

The emphasis on energy conservation leads to over-reaction on the part of analysts and observers of air transportation. The fuel-conserving potential of various measures which have been conceived tends to be overstated because individual measures are often combined and applied to the air transportation system without regard to their logical implementation within the system. Furthermore, the benefits of such measures are often accepted without due consideration of the costs associated with their eventual implementation.

Accordingly, the present study was undertaken to evaluate alternative fuel conserving measures in a systematic way such as to reveal the realistic potential of discrete options with due regard for their economic, social, and environmental costs, as well as for their fuel-conserving benefits. Such an analysis will assist NASA in the formulation of a cost-effective R&D program in energy conservation.

Objectives

The primary objective of the study can be most succinctly stated as follows:

- Evaluate alternative fuel-conservation options as applied to the domestic air passenger transportation system

Collateral objectives include:

- Determine the quantitative effects of implementing selected fuel-conservation options on:
  - fuel required by commercial air transportation,
  - travel demand, and
  - fleet requirements out to the year 2000
- Investigate impacts of these fuel-conserving options on airlines, manufacturers, airports, Government, and air travelers
- Consider regulatory implications of selected fuel-conserving options

Study Scope

An understanding of the scope of the UTRC study requires an appreciation of the overall study organization as structured by NASA. In all, four contractors were selected to carry out separate but interdependent studies. They included two airframe manufacturers: Lockheed-California Co. (LCC) and Douglas Aircraft Co. (DAC); one operator: United Airlines (UAL), and one consultant: United Technologies Research Center (UTRC). Although these participants had separate contracts, the nature of the assigned tasks was such as to require close coordination throughout the study, including mutual agreement on ground rules and methodology, as well as sharing of data. The division of responsibility among the RECAT contractors can be generally summarized as follows:

Contractor	Primary Responsibility
Manufacurers	Aircraft design: modifications, derivatives, new aircraft
Operator	Design review; documentation of current aircraft
Consultant	Demand & fleet forecasting; benefit/cost analysis of fuel-conserving options

Fuel-Conservation Options

The UTRC responsibility, as stated above, involved the evaluation of a baseline scenario and five broadly defined fuel-conserving options, where most of these options also included suboptions to definitively evaluate specific alternatives under each broad heading. The entire set of fuel-conservation options is summarized in Table I, where for convenience the baseline scenario and its variations have been labeled as Option I, Ia, and Ib though they are not fuel-conserving options in the same sense as the others listed.

The fuel-conservation options break down into four broad categories: improved operating procedures; retrofit to or modification of existing aircraft models; derivative models of existing aircraft; and newly designed aircraft. The baseline case considers the nominal evolution of the present air transport system in

TABLE I

KEY TO UTRC FUEL-CONSERVATION OPTIONS

Option		Aircraft Available for Assignment
Ia	Baseline	Baseline In-Prod. Models* (BIPM)
	Baseline Sensitivities	
	Ia 60¢/gal Fuel	BIPM
	Ib Fuel Allocation LF = 70%	"
IIa	Operating Procedures: Present ATC	BIPM
IIb	" " : Advanced ATC	"
$IIIa_0$	Retro/Mod: In-Prod. only	BIPM
$IIIa_1$	" " : Aero; Proj. Ret'm'ts.	"
$IIIb_1$	" " : Aero + Eng; Proj. Ret'm'ts.	"
$IIIa_2$	" " : Aero; Delayed Ret'm'ts.	"
$IIIb_2$	" " : Aero + Eng; Delayed Ret'm'ts.	"
IVa	Basic Derivative Option	BIPM +: DC-9-30D1;DC-10-10D;L1011L
IVb	Without L-1011L	" + " "
V	New Near-Term Aircraft	BIPM +: N80-200I; N80-400L
VIa	New Far-Term TP: Pre-1985 Intro.	BIPM +: N85-200P
VIb	" " " ": 1985 Intro.	" ": N85-200P
VIc	" " " TFs	" ": N85-200; N85-500
VId	" " " TP + TF	" ": N85-200P; N85-500
VIe	" " " TPs (estimate)	" ": N85-200P; N85-500P (est)

* DC-9-30; B-737; DC-10/L1011; B-747-200; B-727-200

the absence of further fuel-conservation measures. Moreover, in view of the uncertainty of fuel price and availability in the future, several cases were studied with baseline assumptions except for higher fuel price and/or restricted fuel availability. In all cases, forecasts were made for the years 1980, 1985, 1990, and 2000, and comparisons were made with the base year, 1973. The specific features of each option are summarized as follows.

In the baseline option (I) only those aircraft listed in the footnote (BIPM) were assumed to be available as replacements for retired airplanes and to accommodate demand growth in the forecast years. As conceived, the baseline option represents an extension of present aircraft usage into the future. No fuel-conservation measures are enforced, beyond those already being practiced by airlines in 1973, and no new or derivative aircraft are introduced in the forecast period which extends to the year 2000. Although this definition of the baseline option is severe in that these assumptions are quite conservative and probably not realistic, it does represent a tractable datum from which to measure the effects of system improvements on fuel consumption. Furthermore, the range of seating capacities covered by the baseline aircraft is broad enough (92 to 386 seats) to keep flight frequencies within manageable bounds. These same airplanes were retained as competitors to new and derivative aircraft in Options IV to VI; i.e., the fleet forecasting model was presented with a mix of available aircraft, for assignment to each route, which always included at least the baseline in-production airplanes.

A set of sensitivities has also been examined for the baseline case. The effects of increasing fuel price on demand, fuel usage, and fleet composition were examined, as were the effects of scenarios in which fuel is assumed to be scarce to the extent that it is allocated, in varying amounts, to the air transport system.

The Operational Procedures Option (II) was included to obtain an estimate of the fuel savings achievable by improvements in airline operations. These improvements are divided into two categories: Option IIa, which incorporates airline operations and maintenance measures compatible with the present ATC system through relatively minor adaptations, and Option IIb, which combines these measures with an improved ATC environment assumed to be in existence by the mid-1980's.

Options featuring retrofits or modifications of existing airplanes (Option III) are also divided into two categories: Option IIIa includes aerodynamic modifications specifically tailored to each of the baseline in-production aircraft, and Option IIIb includes these aerodynamic changes plus replacement of JT4 and JT3D engines with refanned JT8D engines on first-generation turbojet and turbofan models. In each case, the lifetimes of the retrofitted airplanes are extended to reflect the additional investments incurred by these modifications. Furthermore, new additions to the fleet also include the changes, so that the entire fleet incorporates the retro/mod features by the 1985 forecast year.

Derivatives of the DC-9, B-727, L-1011, and DC-10 airplanes were designed by the manufacturers for Option IV. These derivatives compete with each other and with their own baseline models for assignments to the 600 city-pair routes in the demand and fleet assignment process. Although introduced in 1980, these aircraft are not assumed to be in airline service in large numbers until 1985.

The new, fuel-conserving, aircraft designs based on current technology (Option V) and advanced technology (Option VI) are introduced in the early and late 1980's, respectively. The near-term designs include aerodynamic and structural improvements over the baseline aircraft (e.g., supercritical wings and use of composites in secondary structure elements) and advanced turbofan engines as represented by the JT10D and CFM56. Further advances are assumed for the far-term aircraft, including extensive use of composites in the primary structure, active controls, and turboprop engines of advanced design.

Relationship to NASA Programs

NASA has traditionally played an important role in providing the technology which formed the basis for the U.S. dominance in the air transport field. The ongoing NASA R&T program has sought to be responsive to the needs of the air transport industry well into the future. Thus, the energy crisis, as it suddenly reached the awareness of the public in late 1973, was already being met on many fronts in the ongoing NASA R&T program. Nevertheless, the added urgency of the problem, as it was so dramatically displayed, sparked new interest in energy conservation as it could affect aircraft fuel usage. Several new programs aimed at improved conventional and unconventional engines, use of alternative fuels, and increased structural and aerodynamic efficiency, were initiated.

In addition, a task force on "Aircraft Fuel Conservation Technology," headed by J. J. Kramer, of OAST, was established in February 1975 to consider technological measures which could improve aircraft fuel efficiency. The report of that committee, issued in September 1975, outlined a recommended R&T program involving advanced propulsion, composites in primary aircraft structures, and the use of laminar flow control. The effect of these improvements was evaluated by assuming a timetable for their introduction and computing the potential fuel saving out to the year 2005.

While these results provide an upper limit on fuel savings achievable, a more conservative estimate must account for the introduction of new technology at a rate which is acceptable to the users on the basis of economics and environmental compatibility and with due regard for the effect of innovations on travel demand.

The present study attempts to add this degree of realism for those technological advances which are common to both studies. However, a one-to-one correlation between the two studies is not possible because they were done separately with different ground rules and this study did not include all of the advanced technology considered in the task force report. Nevertheless, the studies are complementary in nature and, taken together, aid in the formulation of an R&T program which will improve the fuel economy of future commercial air transports.

Approach

The approach to the study can be stated simply. Each fuel-conserving option (including the baseline) was treated as a discrete scenario for the future. Each option is characterized by aircraft with known performance and economic characteristics. These data permit the initial calculation of the required fleet to satisfy the estimated travel in a representative air transport network for several future forecast years. However, since the definition of the fleet will affect fare, frequency, and trip time which, in turn, will affect travel demand, the fleet assignment process must be performed iteratively with the passenger travel forecast before convergence on the required fleet for each fuel-conserving option. Once convergence is achieved, the system and all of its characteristics, including fuel consumed, can be computed. These characteristics, useful in themselves for evaluation of alternative options, are also used as input to a benefit/cost analysis in which benefits in fuel saving can be evaluated in relation to other criteria to result in a benefit/cost rating which is a single, global measure of the relative merit of alternative fuel-conserving options.

RECAT Model Structure

The process in which this evaluation is carried out is schematically displayed in Fig. 1. The main parts of the program -- the O-D passenger forecast, the fleet composition, and the benefit/cost analysis -- are outlined in shaded boxes, and all important factors involved in the analysis are shown with arrows indicating either their effects on other factors or their input to major elements of the program.

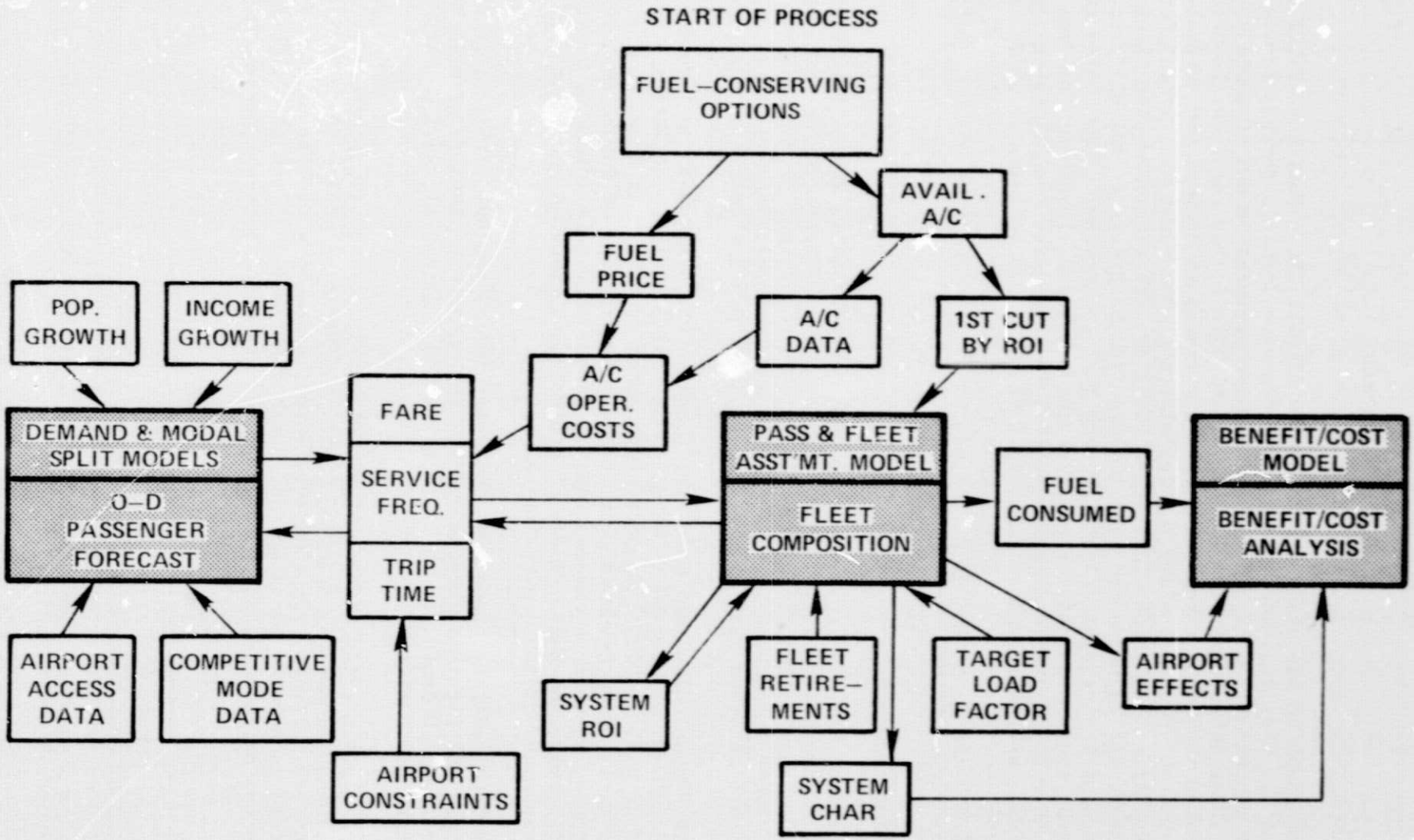
The passenger demand and modal-split models which are used to forecast origin-destination (O-D) air demand in a multimode travel environment were previously developed as part of UTRC's Corporate-sponsored program. As shown on the left-hand side of Fig. 1, these programs accept inputs descriptive of future population and income growth, as well as characteristics of the candidate intercity travel modes (air, auto, rail, and bus). These characteristics affect a passenger's choice of mode as expressed by the disutility* of travel.

The second modeling procedure, indicated in the center of Fig. 1, is the passenger demand and fleet assignment model. The purpose of this program is to convert the forecasted O-D demand to an estimate of the required aircraft on each route in the air transport network.

Each fuel-conserving option (uppermost box in Fig. 1) is described by a set of aircraft which may include existing types, modification and/or derivatives of these types, and new aircraft. In addition, a fuel price or a fuel allocation scheme may be specified as part of the scenario. Data descriptive of the aircraft are used as inputs to the calculation of operating cost, and also to make a preliminary aircraft

*Disutility is defined as either the total cost of travel (out-of-pocket cost + travel time x value of time) or the total time of a trip (travel time + out-of-pocket cost/value of time).

RECAT SYSTEM MODEL



76–03–113–2

FIG. 1

R76–912038–17

selection (for each route) on the basis of return on investment. (An alternative means of making the assignment is to use fuel consumption rather than return on investment as the assignment criterion. This criterion would be used, for example, in a fuel-allocated scenario.) In addition to achieving the best economic performance among those aircraft available in the fleet, a mix of aircraft is selected so as to include a range of passenger capacities.

The operating costs of the airplanes affect the fare level, which is chosen to provide an acceptable ROI (12 percent) for the total system. Similarly, the trip time and service frequencies appropriate to each route, based on the aircraft assigned in each case, provide the necessary inputs for a refinement of the initial estimate of the O-D passenger demand. When this revised demand is used in the passenger and fleet assignment model, a new fleet is composed, and then the process is repeated until convergence is achieved; i.e., demand, fare, and system ROI are in equilibrium.

Results for a particular fuel-conserving option provide a "snapshot" of the total system from which values of important system parameters can be selected. Certainly, total fuel consumed is one of these but, in addition, such quantities as total investment in new aircraft, user costs (fare), operations required at busy hubs, etc., are of interest. Knowledge of the system's characteristics provide necessary inputs to the last of the three modeling procedures indicated in Fig. 1, a Benefit/Cost Model. Using this model, which was developed at UTRC prior to the RECAT study, a benefit/cost analysis is performed in order that the implications of each option can be viewed in terms of its impact on the system, and to put fuel consumption into perspective with other system costs.

Study Ground Rules and Data Inputs

The study results are, of course, dependent on the assumptions accepted by the study participants and the aircraft data provided as input to the fleet forecasting models. A listing of the study ground rules is given in Table II, and an abbreviated summary of the airplane characteristics used in the fuel-conserving options is presented in Table III.

TABLE II
RECAT STUDY GROUND RULES

Seating

- 10%/90% first class/coach split
- 38-in. pitch first class; 34-in. coach
- Lower-level galley, no lounge in wide-body a/c
- Base year: 8-abreast DC-10/L1011; 9-abreast 747
- F'cst yrs: 9-abreast DC-10/L1011; 10 abreast 747

Cargo & Pass. Allowances

- Cargo 10% of revenue
- Passengers 200 lb., including baggage

Economic Parameters

- All costs in 1973 (base year) dollars
- Inflation 5%; discount rate 8%
- Spares allowance 15% flyaway cost
- New a/c breakeven production run 250 a/c
- Depreciation period 16 years

Operations Parameters

- Nominal load factor 58%
- Operating cost: DOC - ATA updated
  IOC - Lockheed

(Adjusted by UAL for service experience)

Hub Constraints

- For stage lengths under 800 mi, no wide-body a/c larger than DC-10/L1011 assigned to New York (LGA) and Washington (DCA)

Fares

- The following yield curve was used; incorporates effects of CAB Phase 9 adjustments. Base-year discount levels assumed for forecast years

Dist. (st.mi)	Base year ($/pass)	F'cst Yrs. ($/pass)
0	7.70	8.50
500	41.80	44.10
800	59.30	60.30
1000	70.80	69.20
1200	82.50	79.60
1600	101.90	96.80
2200	130.90	123.10
3300	154.00	144.30

- Hawaii yields are $0.0418/pass-mi

TABLE III

SUMMARY OF AIRPLANE CHARACTERISTICS

Series	Airplane	Other Airplanes Represented	Capacity Seats (1980-2000)	Max* Stage St. Mi.	Year of Introduction, Yo	1973 Fleet Size (600 city-pair)	Flyaway** Cost 10^6	Flyaway Cost/ Seat $/seat
Baseline: Out of Production	DC-9-10		70	1400	1966	46	4,100	58,600
	B-727-100		102	2010	1966	286	7,880	77,300
	DC-8-50	B-707-120B, B-720B	139	3480	1961	139	8,600	61,900
	DC-8-62	B-707-320B	149	5640	1967	89	8,940	60,000
	DC-8-61		198	3470	1967	39	10,300	52,000
	DC-8-20	B-720, DC-8-30, CV-880	139	3035	1958	89	7,210	51,900
	Turboprop	CV-580/600, F-27, FH-227	45	300		13	0,930	20,700
Baseline: In Prod.	DC-9-30		92	1200	1967	172	5,150	56,000
	B-737-200		97	865	1970	87	5,620	57,900
	B-727-200		132	1795	1968	247	8,490	64,300
	DC-10-10	DC-10-40, L-1011-1	275	3240	1972	100	20,130	73,200
	B-747-200	B-747-100	386	5400	1970	65	29,100	75,400
Aero Retrofit	B-737-200R		97	865	1978	0	5,700	58,800
	DC-9-10R		70	1400	1978	0	0,080	--
	DC-9-30R		92	1200	1978	0	5,230	56,800
	B-727-100R		102	2010	1978	0	0,080	--
	B-727-200R		132	1795	1978	0	8,570	64,900
	DC-8-50R	B-707-120B, B-720B	139	3480	1978	0	0,150	--
	DC-8-62R	B-707-320B	149	5640	1978	0	0,150	--
	DC-8-61R		198	3470	1978	0	0,150	--
	DC-8-20R	B-720, DC-8-30	139	3035	1978	0	0,150	--
	DC-10-10R	L-1011-1	275	3240	1978	0	20,410	74,200
	B-747-200R	B-747-100	386	5400	1978	0	29,380	76,100
Aero/Engine Retrofit	DC-8-20ER	B-720, DC-8-30	139	3035	1979	0	4,650	--
	DC-8-50ER	B-707-120B, B-720B	139	3480	1979	0	4,870	--
	DC-8-61ER		198	3470	1979	0	4,870	--
	DC-8-62ER	B-707-320B	149	5640	1979	0	4,870	--
Derivative	DC-9-30D1		117	1200	1980	0	8,510	72,700
	DC-9-30D2		122	1600	1980	0	10,200	84,300
	B-727-300		156	2270	1979	0	13,900	89,100
	DC-10-10D		199	2540	1980	0	18,077	90,800
	DC-10-40D		327	3390	1980	0	35,879	109,700
	L-1011-LONG		407	2095	1980	0	26,920	66,100
	L-1011-SHORT		200	1855	1980	0	19,100	95,500
New Near Term	N80-200-I		200	1450	1980	0	17,284	86,400
	N80-200-L		200	2900	1980	0	19,706	98,500
	N80-400-L		400	2895	1980	0	30,471	76,180
New Far Term	N85-200		201	2940	1985	0	16,560	82,400
	N85-350		357	2940	1985	0	29,000	81,200
	N85-500		512	2940	1985	0	35,310	69,000
	N85-200P		200	1440	1985	0	16,775	83,900

* As supplied by UAL for 90% winter wind condition.

** Includes 15% for spares. For out-of-production Retrofit Aircraft, tabulated cost is for retrofit only.

SIGNIFICANT RESULTS

Although the major objective of this study has been to compare technological alternatives to achieving fuel conservation in the air transportation system, it has been shown that "actual" fuel usage is not the only consideration. If it were, then a solution which incurs enormous cost to the system, thereby raising operating costs and fares, thus reducing demand, would appear most attractive. Obviously, some balance must be struck between absolute fuel savings and maintenance of a viable air transportation system.

Comparative Measures

In this study, several devices have been used to express the relationship between fuel usage and system costs. Fuel efficiency, expressed in passenger-miles (or seat-miles) per gallon of fuel used, is a parameter which is appropriate to measure system performance as regards the way fuel is used. In effect, it modifies the parameter "actual fuel used" by introducing demand served as a consideration of equal importance. However, the drawback to fuel efficiency as a comparative measure is that it cannot be used to determine cumulative fuel used.

Another device which was employed in the presentation of results is "adjusted" fuel usage, which is the fuel which would be used to satisfy the baseline demand at the fuel efficiency of the particular option being examined. With this parameter it becomes possible to compare options on the basis of cumulative fuel, and the problem of demand variations among options is eliminated by normalizing demand to the baseline value in each case. Thus, adjusted fuel used is a convenient measure because it permits an estimate of the "savings" in fuel relative to the baseline case.

Finally, the use of benefit/cost ratios has been utilized because it is a means of bringing additional considerations, such as noise, emissions, and government spending, into the comparisons. Fuel, user cost, and trip time enter, directly or indirectly, into the calculation of disutility which determines demand. Therefore, these parameters have an implicit effect on fuel used (actual or adjusted) and on fuel efficiency. However, noise, emissions, and government spending do not enter into the calculation of these other measures; they are considered only in the benefit/cost analytical process.

Comparison of Fuel-Conserving Options

In an attempt to summarize the totality of results for all options and to compare the fuel-conservation potential of each alternative, a set of summary charts has been prepared in which the measures noted above have been employed. General results for cumulative demand, cumulative fuel saved, and gain in average fuel

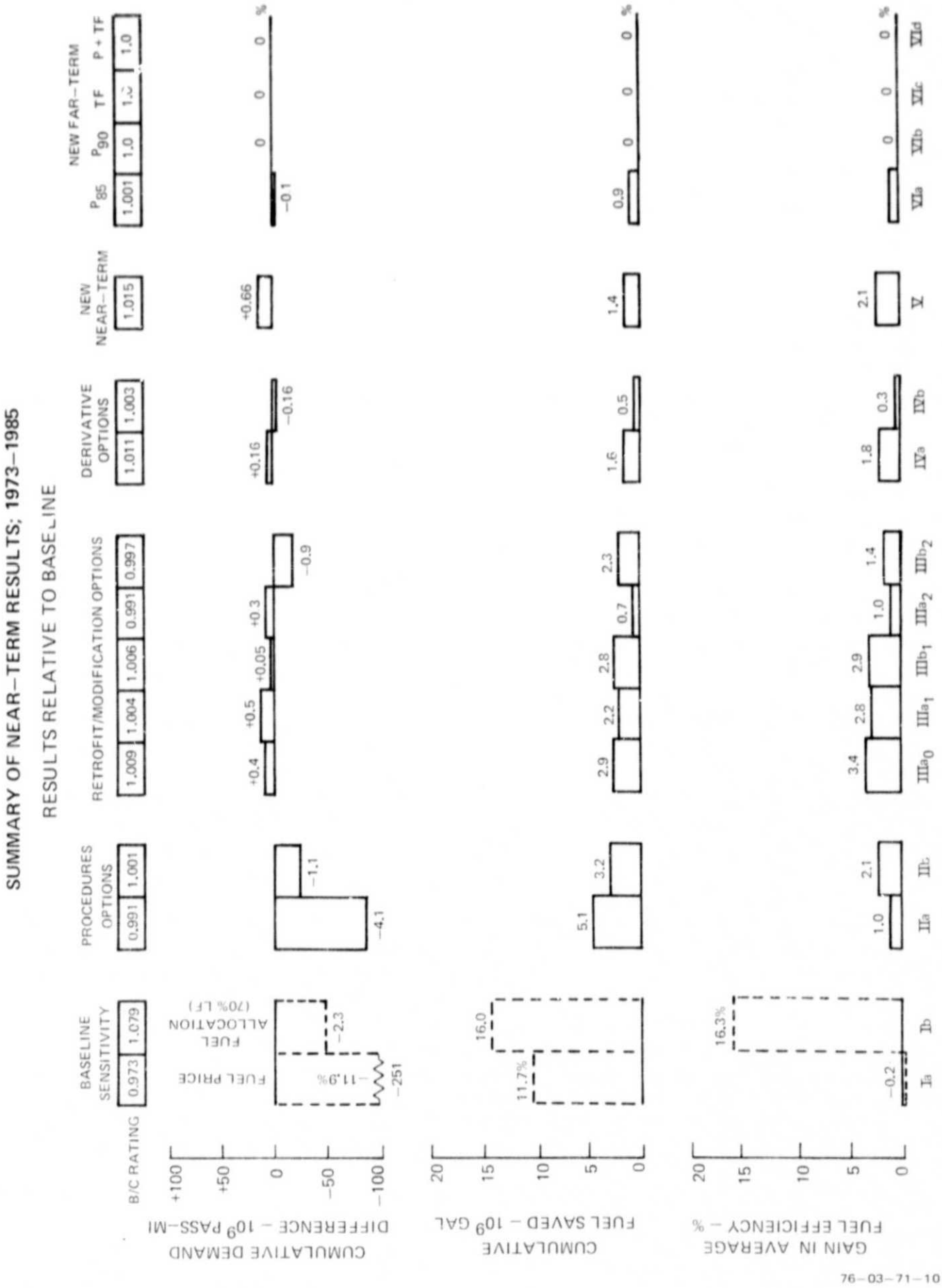
efficiency (average fuel efficiency is defined as the ratio of cumulative demand to cumulative fuel used) are presented for the near term (1973-1985) in Fig. 2, and for the far term (1973-2000) in Fig. 3. These charts, which also give the benefit/cost ratings for each option, express the differences of each parameter relative to the baseline case, giving not only the absolute difference in the cumulative parameters (on the scale), but also the percentage differences (on each bar). An additional chart, Fig. 4, provides summaries of actual and adjusted cumulative fuel savings for selected options over various segments of the forecast period.

Considering first the near-term results in Fig. 2, note that, in terms of "goodness", all parameters have been selected to be better when they are positive and numerically high. In the case of benefit/cost ratings, numbers greater than 1.0 indicate an improvement relative to baseline values, whereas, in the other parameters presented, numbers greater than zero represent improvements. Also, results for the baseline sensitivity options are indicated by dashed lines to differentiate them from the technology-oriented results. Since fuel price and load factor variations may also be applied to any other option, these results are not meant to suggest alternatives to the technology options but additive effects which could be expected if these measures were adopted in combination with the other options. Therefore, their inclusion is primarily for reference rather than comparison.

The near-term results show that differences among the technology options are relatively small. Since derivative and new-aircraft fleets are rather small up to 1985, the beneficial effects of these advanced-technology options are not evident in Fig. 2. Respectable fuel savings are achieved by the operating procedures and retrofit/modification options, but the largest of these savings (IIa) is clearly due to depressed demand. This leaves only retrofit and modification as practical methods of conserving fuel in the near term. Of the five retrofit/mod options studied, the best are: $IIIa_0$, in which no retrofits to out-of-production aircraft are performed, and baseline retirement schedules are used; and $IIIb_1$, in which both aerodynamic and engine retrofits and modifications are performed with retirement schedules for out-of-production aircraft delayed only slightly (3-5 years) from the baseline.

Far-term results, as depicted in Fig. 3, are quite different from near-term results. Improvements occur in all cases, but the optimum derivative and new-aircraft options gain proportionally more than Options II and III. The end result is that the options tend to improve with advancing technology level, i.e., toward the right in the figure. It is noted that the retrofit/mod options merge to a common result in the long term, with cumulative fuel savings of about 5 percent and average fuel efficiency gains of about 6 percent. However, the advanced-technology options achieve considerably more impressive long-term improvements

FIG. 2


SUMMARY OF NEAR-TERM RESULTS; 1973-1985
RESULTS RELATIVE TO BASELINE
BASELINE SENSITIVITY
PROCEDURES OPTIONS
RETROFIT/MODIFICATION OPTIONS
DERIVATIVE OPTIONS
NEW NEAR-TERM
NEW FAR-TERM
P85
P90
TF
P + TF
B/C RATING
FUEL PRICE
FUEL ALLOCATION (70% LF)
CUMULATIVE DEMAND DIFFERENCE - 10^9 PASS-MI
CUMULATIVE FUEL SAVED - 10^9 GAL
GAIN IN AVERAGE FUEL EFFICIENCY - %
Ia
Ib
IIa
IIb
IIIa0
IIIa1
IIIb1
IIIa2
IIIb2
IVa
IVb
V
VIa
VIb
VIc
VId
76-03-71-10

SUMMARY OF FAR-TERM RESULTS; 1973–2000

ALL RESULTS RELATIVE TO BASELINE

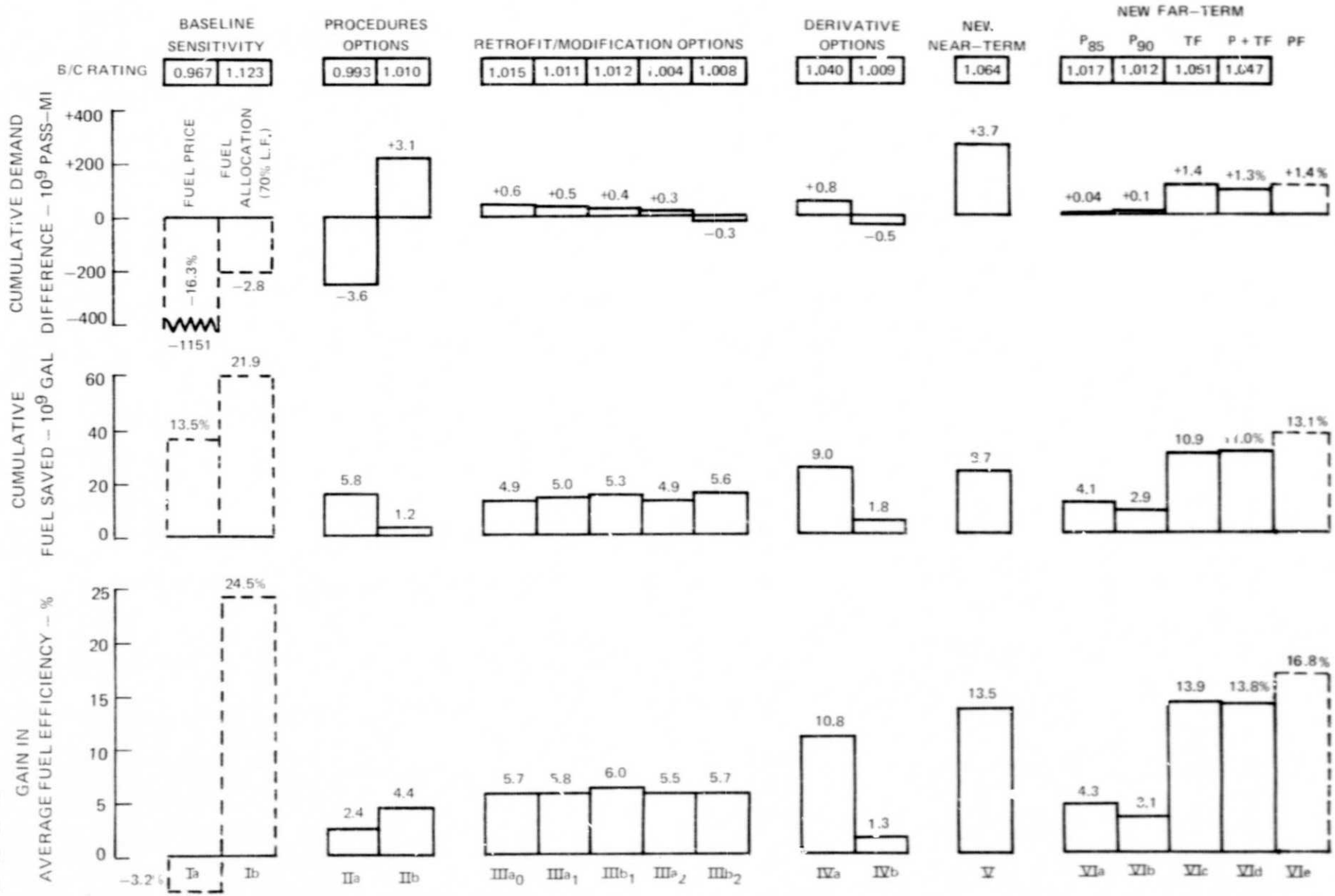


FIG. 3

76-03-71-12

over the baseline case. Particularly notable is Option V which combines the largest demand stimulation with a respectable cumulative saving in fuel and, in terms of average fuel efficiency, ranks with Options VIc and VId. The basic derivative option, IVa, also provides significant improvements over the baseline, and about double the retrofit/mod improvements.

New Far-Term Aircraft Options (VI)

Four far-term fuel-conservation options* were constructed around the new far-term airplanes identified in Table III. The first two feature the N85-200P, introduced either in 1985 (Option VIa) or in 1990 (Option VIb). The nominal introduction period for the far-term aircraft was the mid-1980's, meaning that the first forecast year in which significant numbers could be in service would be 1990. Option VIa was included to test the effect of accelerated R&D on the propfan which might result in a pre-1985 service entry for the N85-200P.

The third far-term option, designated Option VIc, is based on the two turbofan-powered airplanes entering service in the late 1980's. Option VId is similar to VIc except that the N85-200 airplane is replaced by the N85-200P. Although these aircraft have the same seating capacity, the former has a much longer maximum stage length, while the latter is more fuel-efficient at short and intermediate stages. Thus, although only one propeller-driven airplane was provided in the study, it appears in three of the four far-term aircraft options.

Considering the propfan options first, the summary in Fig. 3 shows that early introduction of the N85-200P does have a noticeable impact. The early start in building the N85-200P fleet results in a considerable difference in fuel saved between Options VIa and VIb. In both cases, the baseline airplanes replaced by the N85-200P are the B-727-200 and DC-10/L-1011; larger and smaller baseline airplanes are virtually unaffected.

Fuel savings in Options VIc and VId are considerably greater than in the first two cases. However, this is to be expected because these options involve two new far-term aircraft while the first two options involve only one. Furthermore, the fuel saving advantage of replacing the B-747 with the N85-500 is considerably greater than the corresponding saving associated with replacing other baseline aircraft with the N85-200 and N85-200P. As in the derivative and new near-term aircraft options, much of the fuel savings can be traced to replacement of the B-747 with more fuel-efficient designs, particularly on short, dense routes which require a large-capacity airplane.

* Option VIe was not simulated, but merely estimated. This case is discussed on the following page.

The annual fuel savings achieved in Options VIc and VId become quite large by the year 2000 when almost half the fleet consists of the new far-term airplanes. Although the saving in cumulative fuel used in these two cases does not really take effect until after 1990, the saving in the last decade of the 27-year forecast period is very large, resulting in a 12 percent adjusted saving in fuel over the baseline in both cases. As observed in other options, this latter period tends to dominate cumulative statistics because demand levels are significantly higher than in the early periods -- a consequence of accumulated growth in demand (and, therefore, fuel used) throughout the forecast period.

Comments on Propfan

It is clear from the results of the far-term options that it has not been possible to treat propfan-powered airplanes fairly in this study. To a large extent, this is an unfortunate consequence of the lack of consistent assumptions in defining near-term and far-term technologies, which is, in turn, due to the lack of adequate propfan data at the start of the study. This technology is only now emerging in terms of credible performance information.

The results of Option VI may appear to conflict with data which show the N85-200P to compare favorably with the N85-200 in fuel efficiency. Moreover, the better fuel efficiency of the N85-200P occurs in spite of the fact that it does not benefit as much from advanced airframe design (use of composite materials) as the N85-200. However, the N85-200 also has the advantage of a much greater range, thereby permitting it to compete on many more routes. For this reason, its impact was greater, although the differences between Options VIc and VId, from which the impacts of these airplanes can be compared directly, is quite small.

As noted earlier, the lack of a large-capacity airplane with propfan power is a major impediment to Options VIa and VIb. On this basis alone, a comparison of results among the far-term aircraft options, or between the propfan cases and other options, is not valid. In this regard, it might be argued that, on the basis of comparable airframe technology, Option VIc might better be compared with Option V. However, lack of a large-capacity propfan-powered design precludes a fair comparison, even in this case.

Therefore, it appears that further analysis is required to determine the true potential of the propfan as an alternative to the turbofan. In view of the attractive fuel efficiency of the N85-200P, it is probable that this potential is significant if properly exploited. For example, if it is assumed that a large propfan-powered airplane would have the same fuel efficiency advantage over a turbofan-powered airplane as it has in the 200-passenger size, and that the economic performance is about the same, results for an all-propfan case can be estimated as shown in Case VIe of Fig. 3. These results, which are indicated by dashed lines to identify them as estimates, show that significant fuel savings may be achieved with propfans.

Fuel Savings From Large-Capacity Aircraft

For many of the options where large savings in fuel are shown, one of the most important factors has been the replacement of the B-747 on short routes where that airplane is not fuel-efficient. In view of the major role this changeover assumes in the study, it is important to understand how it comes about.

Of paramount importance is the study assumption concerning the future capacities of major hub airports. Data supplied by UAL for ten major hub airports suggested only about a 25 percent expected increase in overall capacity for air carrier movements over 1973. The implication of this estimate is that an increase in demand of more than 25 percent can be accommodated only by an increase in average seating capacity of aircraft if extreme congestion is to be avoided. Even if this estimate is conservative, very large increases in capacity will be required to handle the demand growth forecasted out to the year 2000.

Using the estimate provided by UAL as a guideline, the frequency rules used in the fleet assignment program were conceived to restrain growth in air carrier movements, particularly on the densest routes which invariably involve one or more major hub airports. The result is that the aircraft assignment algorithm tends to favor large airplanes on dense routes and small airplanes on lightly traveled routes. Furthermore, many of the densest routes are of relatively short stage length.

The result was assignment of the B-747 to many short-haul routes in the baseline case. On some important routes, namely short stages involving New York or Washington, D. C., the B-747 is ruled out because of limitations at LaGuardia and National Airports. This means that frequencies on some other routes must be further constrained to avoid congestion, thereby resulting in even more extensive use of wide bodies like the B-747.

An important implication of the use of the B-747 is its relatively poor fuel efficiency at short stage lengths. A consequence is that the advanced, more fuel-efficient large aircraft achieve a great fuel saving when assigned to replace the B-747. This result leads to two significant conclusions: 1) the greatest fuel savings are achieved by large airplanes, and 2) a large airplane with good fuel efficiency at short stage lengths can have a great impact on fuel savings.

Benefit/Cost Ratings

When consideration is taken of the benefit/cost ratings, the above comparison of options need not be qualified. In the near term, Fig. 2 shows that the ratings are all very close to 1.0, and those technology options which appear most attractive ($IIIa_0$ and $IIIb_1$) do not suffer from the additional considerations included in calculating the benefit/cost ratios. There are, however, some gains in relative ranking by Options IVa and V which place them in a slightly more favorable light. Considering its moderate fuel saving and superior benefit/cost rating, Option V may be a good near-term alternative from this broader perspective.

In the long term, (Fig. 3) the fuel-saving advantages of the advanced-technology options are further augmented by their high benefit/cost ratings. Furthermore, it appears that Option V achieves a slight edge because it has the highest benefit/cost rating (due to much lower Government spending relative to Option VI) and close to the highest fuel efficiency.

Thus, despite the many additional factors considered in the benefit/cost analysis, the implications are not significantly different than were found in the earlier comparison made primarily on the basis of fuel saved, thereby enhancing the confidence with which the study results can be regarded. This rapport is fortunate because it means that striving to save fuel is not inconsistent with efforts to improve the overall air transport system as measured by benefit/cost ratings.

Actual and Adjusted Fuel Savings

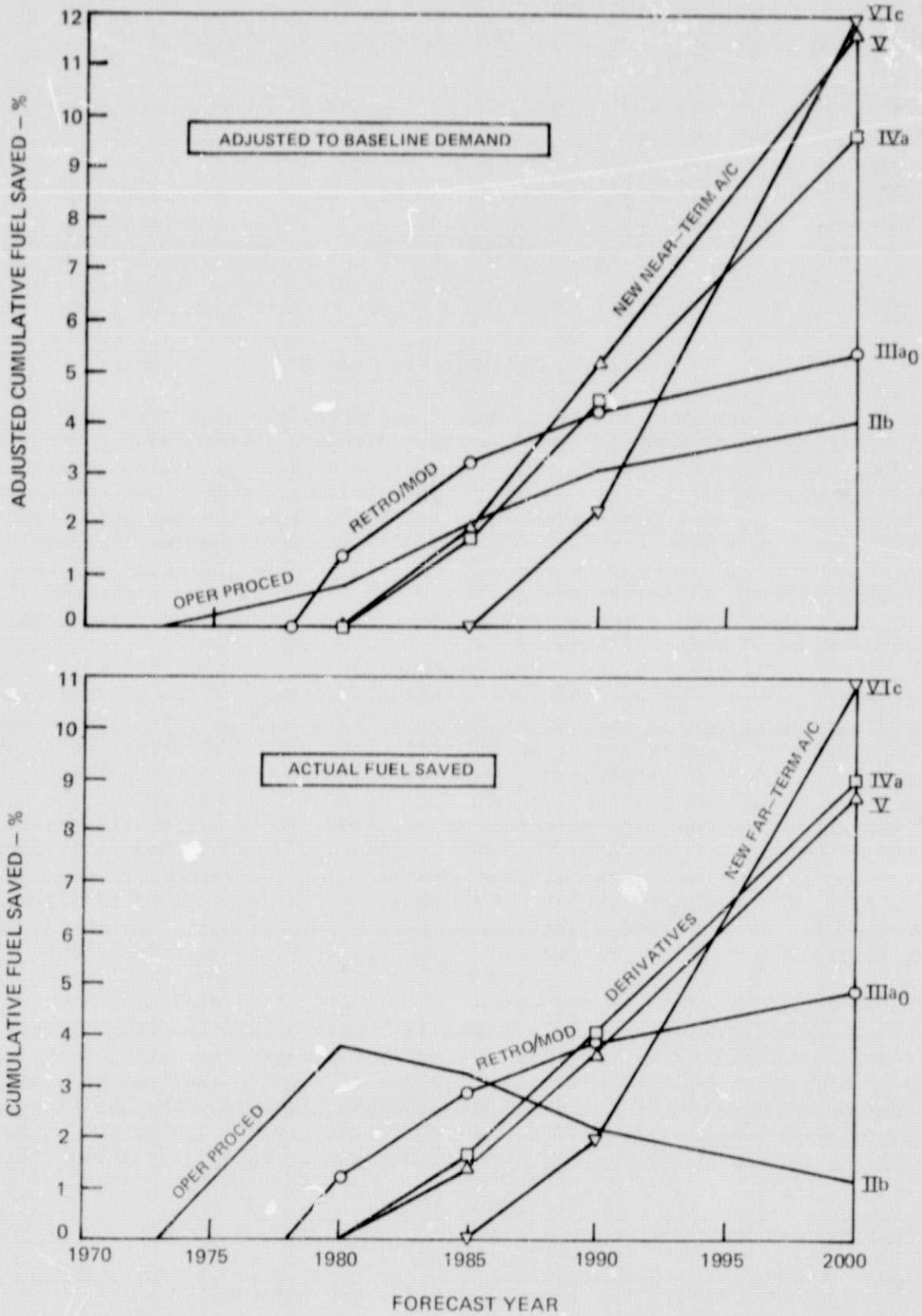
Some additional insights can be gained by comparing the options on the basis of actual and adjusted cumulative fuel savings continuously over the forecast period. This comparison is made in Fig. 4 for those technology options which achieved the best results in Figs. 2 and 3. The advantage of this presentation is that it makes possible a determination of the best option for any period out to the year 2000. Rankings in actual fuel saved in the previous two figures appear on the bottom half of Fig. 4 for 1985 and 2000. Also indicated are the numerical standings for all other years. Since the curves intersect in many places, it is apparent that these numerical rankings are strongly dependent on the period of years chosen.

Furthermore, it can be seen that the relative standings of the various options are not the same for adjusted savings as they are for actual savings. Since actual savings may be somewhat deceptive as an indication of fuel efficiency, the adjusted savings provide the better comparison. Based on this measure, three options (IIb, $IIIa_0$, and V) are the best alternatives for fuel conservation throughout the period. However, whereas IIb is the best choice up until 1979*, it is ultimately the worst choice (among the options depicted) by 2000. Similarly, Option V does not emerge as the best choice until 1988, and although Option $IIIa_0$ is dominant in the middle period, it is a poor long-term choice. Note that, at the very end of the forecast period, Option VIc becomes better than Option V by a small amount. However, due to the steep slope of the Option VIc curve, it would predominate in later years.

Although Fig. 4 is probably the single most descriptive exposition of the results which emerge from this study, it must be interpreted with care. Because the individual options defined for this study are very selective, i.e., each one specifies a particular fuel-conservation alternative, and combinations of options are not considered, not one of the individual options, including the baseline, can be thought of as a future scenario. Therefore, the interpretation of Fig. 4 must be that the savings indicated for any given option are probably the minimum that

* For the period prior to 1980 Options IIa and IIb are the same.

CUMULATIVE FUEL SAVED THROUGH TECHNOLOGICAL OPTIONS



76–03–71–11

might be achieved. Additional savings can be achieved if certain options are combined, particularly if system improvements, such as Option IIb, are combined with aircraft technology improvements, such as Options IVa, V, and VI.

Further insight into the relative potential of alternative options can be gained by examination of the fuel efficiency trends presented in Fig. 5. These curves are not cumulative results, as in Fig. 4, nor are they gains over the baseline, as in Figs. 2 and 3; rather, they are actual values of fleet fuel economy for each of the selected options in each of the forecast years connected by smooth curves to show the probable continuity. It is evident that a substantial gain is achieved, even in the baseline case, as brought about by both the ground rules of the study (load factor of 58%, 10/90 first class/coach split) as compared with historical (1973) practice, and the substitution and addition of the more-efficient wide-body aircraft into the fleet. The effects of these measures are felt strongly out to about 1980, but very little further gain is achieved in later years because of the limited opportunity to introduce a greater fraction of the newer aircraft, and because the wide-bodies are used at increasingly shorter stages.

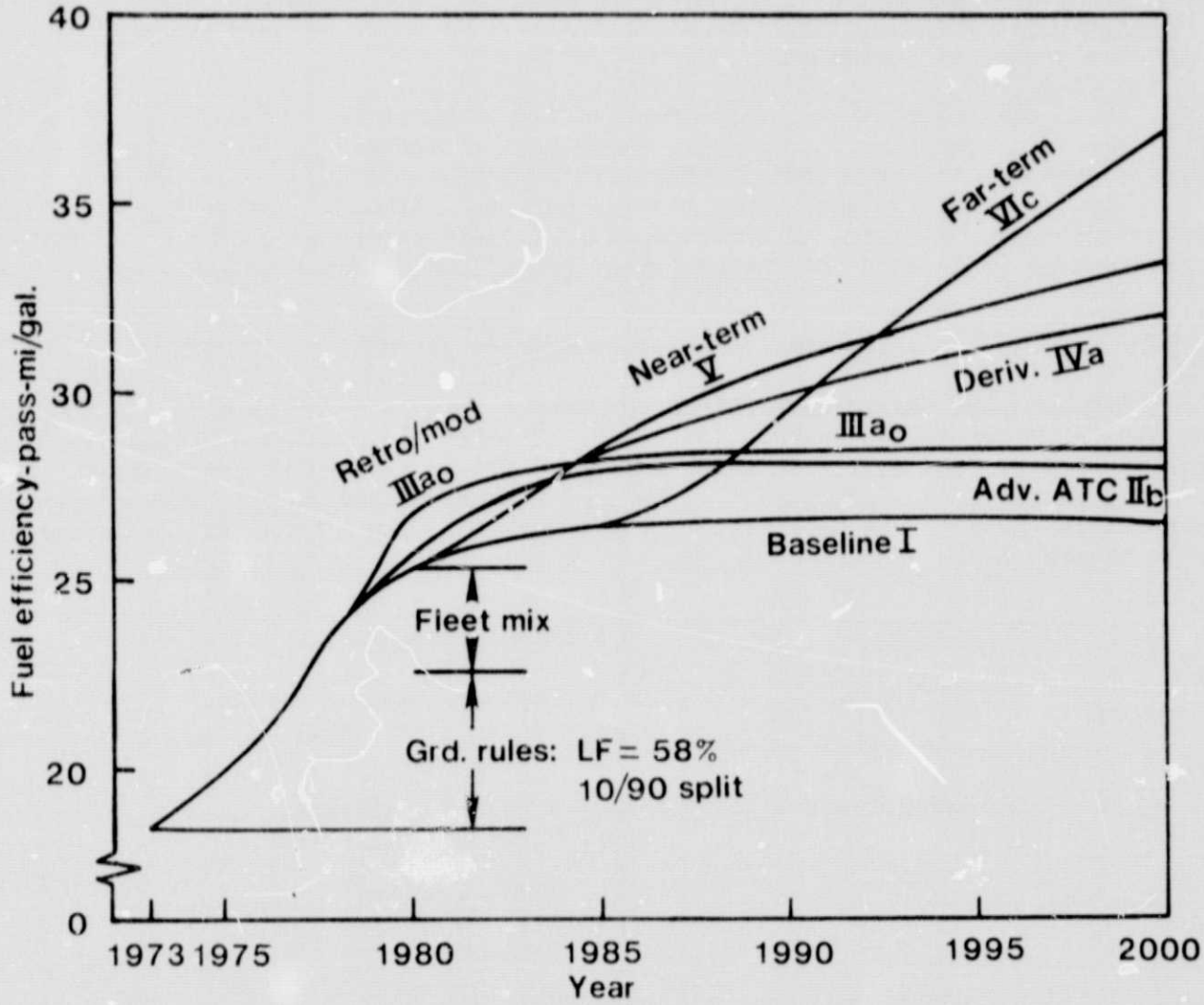
Above the baseline are shown the additional gains in fuel economy achieved by the alternative options. Crossovers among the options are similar to those seen in Fig. 4 except that the effects of the more advanced options show up immediately upon introduction of the option rather than as effects accumulate, as in Fig. 4. Thus, crossovers occur earlier, an effect most noticeable in the case of the far-term aircraft option (VIc) which dominates beyond about 1992 rather than 1999, as in Fig. 4.

Impacts of Fuel-Conservation Options

Although the technology options considered in this study have fuel conservation as the major objective, each option can be expected to impact the various sectors of the air transport industry in other ways as well, in particular, airlines, manufacturers, airports, and government. The impacts were analyzed by isolating particular parameters which affect each sector, where the following list shows the parameters used in each case.

Sector	Impact Parameter
Airlines	Annual Enplaned Passenger-Miles Undepreciated Fleet Value Fleet Seating Capacity
Manufacturers	Annual Aircraft Deliveries Annual Value of Deliveries
Airports	Annual Airport Activity Fuel Capacity Used Noise Exposure
Government	Annual Fuel Used Annual Emissions Cumulative Spending
Air Traveler	Fare Service (Enplaned Pass-Mi)

FUEL EFFICIENCY TRENDS



The impacts are considered in the short term and in the long term, 1985 being used to represent short-term impacts and 2000 for the long-term impacts. All results were computed as percentage differences relative to the baseline case; i.e., the impact measured is the percent change of each parameter relative to the baseline value.

A convenient summary of the impact analysis is presented in Table IV, which provides a qualitative picture in a form which may be readily visualized. Those fuel conserving options which are beneficial to the impacted sectors of the industry in terms of advantages in the chosen parameters are identified by plus (+) signs, where the degree of benefit is roughly proportional to the number of plus signs shown. To avoid redundancy in the visual presentation, several parameters which are somewhat similar to others on the above list have been omitted and, in the case of airline impact, two parameters (passenger-miles and fleet value) have been combined by forming a ratio of the former to the latter, a quantity for which a maximum value is beneficial.

In the short term, the procedures option (IIb) is strongly beneficial to airlines and air travelers, and moderately beneficial to manufacturers. The derivatives option (IVa) is strongly beneficial to the Government, through fuel savings and low spending, and moderately beneficial to airports and airlines. The new near-term aircraft option (V) is strongly beneficial to manufacturers and airports, and moderately beneficial to both the Government and air travelers. The new far-term aircraft option (VIa) though favorable in emissions and noise, should really not be considered in the short term because of its late introduction in the 1973-1985 time period.

In the far term, the weight of beneficial impacts is seen to shift to the right, with new far-term aircraft options (VIc and VId) becoming strongly beneficial to the Government and airports and moderately beneficial to air travelers and manufacturers. Option V is of greatest benefit to the Government. However, even in the long term, the derivative option (IVa) is seen to retain significant benefits for the airlines, the Government (in terms of low spending and moderately low fuel usage), and airports.

Taken altogether, either Option IVa or V appear to offer the greatest short-term and long-term benefits in the 1973-2000 time period. Option IIb, while treated as a separate option in the RECAT study, is in reality not an alternative to one of the aircraft options, but one which could be coupled with any of Options III-VI. Option VI, introduced as it is late in the period, would be expected to show up best in the post-2000 years.

TABLE IV

IMPACTS OF FUEL CONSERVATION OPTIONS

(Beneficial Impacts Indicated by Plus Signs)

Impact	Parameter	IIa	IIb	$IIIa_0$	$IIIa_1$	$IIIb_1$	$IIIa_2$	$IIIb_2$	IVa	IVb	V	VIa	VIb	VIc	VId
					Near Term - 1985										
Airlines	Annual Enplaned Pass-Mi Undepreciated Fleet Value		+++						++		+				
Mfrs.	Annual Value of Deliveries		++	+							+++				
Airports	Hub Capacity Used Noise Exposure			+					++ ++	 +	+++ +++	 +			
Gov't	Annual Fuel Used Annual Emissions Cumulative Spending		 +	++ +++	 +++	 +++	 +++	 +++	+++ + +++	 +++	+ ++ ++	 +++			
Traveler	Fare		+++						+		++				
					Far Term - 2000										
Airlines	Annual Enplaned Pass-Mi Undepreciated Fleet Value		++						+++						+
Mfrs.	Annual Value of Deliveries										+++			++	+
Airports	Hub Capacity Used Noise Exposure								++ +		+ +++			+++ ++	+++ ++
Gov't	Annual Fuel Used Annual Emissions Cumulative Spending		 +	 +++	 +++	 +++	 +++	+ +++	++ + +++	 +++	++ ++ ++			+++ +++	+++ +++
Traveler	Fare Service		++ +++						+ ++		+++ +			++	++

CONCLUSIONS AND RECOMMENDATIONS

Major Conclusions

Arbitrary Fuel-Conservation Measures

Increasing the price of fuel to the operator, whether introduced as a measure to save fuel or by virtue of a bona fide price increase, does not improve fuel efficiency because the required fare increase reduces travel demand more than fuel use.

An arbitrary allocation of fuel is an effective means of reducing fuel and increasing fuel efficiency. The mechanism is an enforced increase in system load factor which, if imposed without a fare decrease, can save significant fuel. However, the effectiveness of fuel allocation is limited to the extent that load factor can be increased without severely affecting service by rejecting demand. Of course, this measure can be combined with technological fuel-conservation measures, discussed below, to augment the effects of both.

Operational Procedures Improvements

Based on the relatively coarse estimates provided in this study, improving operational procedures, particularly if accomplished in conjunction with an improvement in the air traffic control system, may achieve a significant (approximately 4.5 percent) increase in fuel efficiency. The absolute fuel saving is minimal (slightly over 1 percent) because the improvement in service results in an increase in travel. However, this measure can be coupled with technological fuel-conserving measures, and can be implemented in the near term and at relatively low cost.

Modifications to Current Aircraft

The most effective near-term improvement in fuel efficiency is to modify only in-production aircraft primarily with improved aerodynamic features (aerodynamic cleanup, winglets, fairings). Fuel savings of about 3 percent by 1985 are achievable with a fuel efficiency improvement of about 3 1/2 percent. Far-term savings (to the year 2000) rise to about 5 percent but are overshadowed, in that time period, by the potential of other technological fuel-conserving options.

Derivatives of Current Aircraft or New Near-Term Aircraft

Derivatives of current aircraft, specifically a long-body derivative of the L-1011, or new aircraft utilizing current technology, result in about the same improvement in near-term (to 1985) fuel economy (about 2 percent). The benefit is limited because these aircraft cannot be introduced early enough to significantly influence the system in this time period. In the far-term (to the year 2000), these options result in impressive fuel savings (about 9 percent) and increased efficiency

(11 percent for derivative aircraft and 13.5 percent for new aircraft). New aircraft require a significantly greater expenditure by Government and operators but achieve service and environmental benefits to the extent that, of the two approaches, they have the higher benefit/cost rating.

New Far-Term Aircraft

Because they cannot be introduced early enough to have maximum impact by the year 2000, new far-term aircraft show only slightly greater benefit in fuel saving (11 percent) and fuel efficiency (14 percent) by the year 2000 than new near-term aircraft or derivatives. However, because they are fundamentally more advanced aircraft, and because travel will continue to increase in the future, new far-term aircraft would become the preferred option in the post-2000 period.

While the study showed turbofan-powered aircraft to offer greater fuel savings than propfans, this result is not fundamentally valid. Design of propfan aircraft utilizing the same aerodynamic and structural technology as the turbofan aircraft, and in the same size class, would produce slightly better fuel efficiency than that computed for the new far-term turbofan aircraft option.

General

The increase in travel demand, particularly on dense routes, many of which are short-range, requires large aircraft with good short-range economics and fuel economy in order to avoid congestion problems at major hubs which have limited potential for an increase in capacity.

Recommendations

The UTRC portion of the RECAT Study did not provide a strong basis for the formulation of technology recommendations. Technology aspects were treated by the other contractors in the specification of aircraft designs, and these designs were employed in the fleet forecasts. Nevertheless, some of the primary results of the UTRC study do have implications for future research and technology effort.

Rec. No. 1: Design of a large-capacity airplane aimed at good economic and fuel consumption characteristics, specifically for short and intermediate stage lengths

The increase in travel forecast for the future, particularly for the dense routes involving major hubs which have limited expansion capability, requires the use of large aircraft to avoid unduly increasing flight frequency. Despite the fuel savings that were estimated in the derivative- and new-aircraft options, the large-capacity aircraft which generated the savings were not necessarily conceived with good short-stage economics and fuel efficiency primarily in mind. It would appear, therefore, that even greater fuel savings would be achieved if an advanced wide-body airplane were designed specifically for the short- to intermediate-range market.

Rec. No. 2: More precise determination of the cost incurred and fuel saved by improvements in operational procedures

Of all the fuel-conservation alternatives, procedural improvements offer the most immediate fuel-conservation benefits. Even though the fuel savings which are achievable by procedural changes may only amount to a few percent, the fact that early implementation is possible, plus the likely compatibility of procedural improvements with technology advances, makes this alternative worthy of further consideration.

It is recommended that further study be made of operational procedures in order to ascertain the real fuel savings that can be achieved and to identify the costs involved so that the probable implementation of the procedures can be addressed.

Rec. No. 3: Design propfan- and turbofan-powered airplanes with equivalent technology assumptions in order that a fair comparison can be made between these propulsion alternatives

The true fuel conservation potential of the propfan was not determined in the RECAT study because only one propfan-powered design was incorporated in the far-term aircraft options, and because the size and airframe technology assumptions of that design were not entirely compatible with the far-term, turbofan-powered designs. Nevertheless, on the basis of fuel efficiency, the propfan airplane had an advantage over an equal-capacity turbofan airplane. Therefore, there is good reason to believe that fuel would be saved by switching from turbofan to propfan power if the comparison were made equitably. It is recommended that several propfan and turbofan designs be made with seating capacities from 200 to at least 400, and with completely compatible assumptions regarding airframe and engine technology. These airplanes would then be compared as alternative options for further fuel conservation. The more promising propulsor would then be utilized in the scenario comparisons recommended below.

Rec. No. 4: Further study of a realistic scenario (or scenarios) which combine discrete fuel-conserving options for maximum benefit

A final recommendation relates to the question of how to better estimate the actual fuel savings advanced technology will bring. The nature of the RECAT options was quite selective; each one provides an indication of the conservation potential of one particular development and its implementation, but no single option, including the baseline, describes a likely future scenario. Therefore, strategies for future fuel savings cannot be well-formulated on the basis of present RECAT results. Rather, the best RECAT options should be considered in various combinations to determine which options complement each other and which conflict. The potential savings available from an evolutionary strategy in which procedural and technology improvements are viewed together, rather than as alternatives, would provide a firmer basis for research and technology policy formulation. The model assembled in the RECAT study, and the aircraft data which were generated, are well adapted to further analyses of this type.

DATA SUMMARY

It is not possible, in this condensed summary report, to provide more than a small part of the data generated, by UTRC, in the RECAT study. For a complete description of the methodology, discussion of results, and presentation of data, the reader is referred to the final RECAT report, UTRC R76-912036-16.

However, the major results of the study, as presented in earlier sections of this report, were derived from the running of the UTRC Demand and Fleet Forecasting Model. The results of those computer runs have been summarized, for all fuel-conserving options and suboptions investigated, in a series of tables reproduced herein on the following pages (TablesV-XI). These tables are, to a large extent, self-explanatory and help the reader to understand the results summarized earlier.

TABLE V

BASELINE CASE SUMMARY

	Total U.S.* Domestic 1973	600 City-Pair Sample 1973	1980	1985	1990	2000	Avg. Growth Rate: 1973-2000
Total Population - 247 SMSAs (10^6 Persons)	209.6[3]	149.6	161.3	170.5	180.5	196.3	1.0%
Average Income - 247 SMSAs (1973 $/Person/Yr)	5041[3]	5242	6552	7426	8382	11,003	2.8%
Aircraft Fuel Price (1973 $/Gal)	0.1256	0.1256	0.30	0.30	0.30	0.30	
Travel Propensity - (Intercity Trips/Person/Yr)	2.10[4]	2.60	3.11	3.52	3.88	4.86	2.3%
O-D Passenger Demand - All Modes (10^6 Round Trips/Yr)	440.1[4]	139.6	182.7	221.5	260.4	358.3	3.6%
(10^9 Pass-Mi/Yr)	263.2[4]	119.2	164.7	204.3	245.4	352.6	4.1%
Air Share of Total O-D Demand (% of Round Trips)	15.5[4,12]	30.4	36.1	39.7	42.3	48.1	1.7%
(% of Pass-Miles)	43.9[4,12]	61.9	69.4	73.1	75.7	80.6	1.0%
Enplaned Air Passengers (10^6 One-Way Pass/Yr)	177.2[5]	147.4	228.4	303.6	379.7	593.7	5.3%
(10^9 Pass-Mi/Yr)	126.2[7]	107.5	168.8	224.1	280.5	436.1	5.3%
Avg. Growth Rate of Pass-Mi - O-D - All Modes (%/Yr)	-	-	4.7	4.4	3.7	3.7	-
- O-D - Air (%/Yr)	-	-	6.5	5.5	4.5	4.3	-
- Enplaned - Air (%/Yr)	-	-	6.7	5.8	4.6	4.5	-
Business Fraction of O-D Pass - All Modes (%)	20.5[4]	31.5	31.6	31.7	31.7	31.8	0
- Air (%)	54.4[4]	57.9	53.0	50.6	48.7	45.4	-0.9%
O-D Pass Trip Length - All Modes (St. Mi.)	299[4]	427	451	461	471	492	0.5%
- Air (St. Mi.)	693[4]	869	868	850	844	824	-0.2%
Routes with Nonstop Service	?	483	485	494	503	514	0.2%
Air Pass. Carried Nonstop (%)	63.5	89.0	91.4	92.6	93.3	94.1	0.2%
Fares Relative to 1973	1.000	1.000	0.995	0.957	0.950	0.937	-0.2%
Fuel Consumed by Air (10^6 Gal/Yr)	7799[7]	5808	6656	8440	10536	16400	3.9%
Avg. Growth Rate of Fuel Consumed by Air (%/Yr)	-	-	2.0	4.9	4.5	4.5	-
Air System Fuel Efficiency (Pass-Mi/Gal)	16.1	18.5	25.4	26.6	26.6	26.6	1.4%
(Seat-Mi/Gal)	31.1	36.1	45.5	46.3	46.2	45.9	0.9%
Air System Load Factor (%)	51.6[5]	51.2	55.7	57.3	57.7	58.0	0.5%
Activity (Flights/Day)	12456[5]	6615	7328	8240	8959	11103	1.9%
Stage Length (St. Mi./Flight)	443[5]	639	660	677	712	745	0.5%
Aircraft Capacity (Seats/Flight)	121[5]	136	172	192	209	249	2.3%
Fleet Size TOTAL	1853[7]	1372	1549	1771	1992	2557	2.3%
4E WB	60	65	113	227	353	840	
3E WB	98	100	240	340	455	651	
4E NB	401	356	55	0	0	0	
3E NB	627	533	759	845	955	956	
2E NB	490	305	378	360	228	110	
TURBOPROP	177	13	4	0	0	0	

* Superscripts refer to sources in List of References

TABLE VII

FUEL ALLOCATION SCENARIOS
(RECAT 600 City-Pair Network)

	1973	1980					1985			
		Baseline	70% LF_{MAX} 12% POI	70% LF_{MAX} Base Fare	1973 Fuel	50% Base Fuel Incrs.	Baseline	1973 Fuel	70% LF_{MAX} Base Fare	50% Base Fuel Increase
Enplaned Air Pass-Mi (10[illegible])	107.5	168.9	204.9	164.9	165.6	165.9	224.1	215.2	216.0	217.2
Air Pass. Carried Nonstop (%)	89.0	91.4	90.5	89.2	89.6	89.8	92.6	89.4	89.6	90.1
Fares Relative to 1973	1.0	0.995	0.811	0.995*	0.995*	0.995*	0.957	0.957*	0.957*	0.957*
Return on Investment (%)	7.0	12.0*	12.0*	19.2	15.2	12.3	12.0*	22.6	19.0	14.7
Maximum Load Factor (%)	—	58.0*	70.0*	70.0*	62.6	57.8	58.0*	76.8	70.0*	62.5
Average Load Factor (%)	51.2	55.7	68.9	67.0	61.0	56.7	57.13	75.4	69.1	62.0
Total Fuel (10[illegible] Gals/Yr)	5.808	6.656	6.436	5.315	5.807*	6.225*	8.440	5.809*	6.404	7.104*
Increase from 1973	—	14.6%	10.8%	-8.5%	0	7.2%	45.1%	0	10.3%	22.3%
Savings Relative to Baseline	—	—	3.3%	20.1%	12.8%	6.5%	—	31.2%	24.1%	15.8%
Pass-Mi/Gal	18.5	25.4	31.8	31.0	28.5	26.7	26.6	37.1	33.7	30.6
Seat-Mi/Gal	36.1	45.5	46.2	46.3	46.7	47.0	46.3	49.2	48.8	49.3
Flights/Day	6615	7328	6965	6151	6449	6607	8240	6076	6361	6746
Fleet - Total	1372	1549	1449	1259	1327	1365	1771	1246	1315	1402
4E WB	65	113	111	73	82	102	227	86	123	139
3E WB	100	240	340	266	339	396	340	488	522	636
4E NB	356	55*	55*	55*	55*	55*	0*	0*	0*	0*
3E NB	533	759	550	493	486	464	845	322	326	297
2E NB	305	378	388	367	360	343	360	370	345	330
Turboprop	13	4*	4*	4*	4*	4*	0*	0*	0*	0*

* Value held approximately constant (fuel cannot be held exactly constant)

Notes: Baseline: $F_{MIN} = 2 + 3/4\ F_0$ $(F_0 > 8)$
$F_{MIN} = 1 + 7/8\ F_0$ $(F_0 < 8)$
Aircraft ranked by 15% POI load factor

Others: $F_{MIN} = 3/4\ F_0$ (all F_0)
Aircraft ranked by fuel efficiency

TABLE VIII

OPERATIONAL PROCEDURES OPTION
(RECAT 600 City-Pair Network)

	1973 Baseline	1980 Baseline	1980 Present ATC IIa/IIb	1985 Baseline	1985 Present ATC IIa	1985 Advanced ATC IIb	1990 Baseline	1990 Present ATC IIa	1990 Advanced ATC IIb	2000 Baseline	2000 Present ATC IIa	2000 Advanced ATC IIb
Enplaned Air Pass.-Miles(10^9)	187.5	188.8	189.3	202.1	214.3	215.2	280.9	290.1	293.7	426.1	442.6	456.5
Fuel – Total (10^9 gals)	5.805	6.656	6.167	8.346	7.821	8.422	10.536	9.528	10.500	15.148	13.438	15.376
– Savings vs. Baseline (%)	–	–	7.6	–	6.7	8.1	–	6.3	0.3	–	8.8	8.1
– Efficiency – pass. – mi/gal	28.52	25.37	25.74	26.55	27.38	27.69	26.64	30.37	28.01	28.18	28.34	28.94
– Efficiency – seat – mi/gal	36.15	49.53	46.72	46.32	43.87	46.82	46.17	42.69	48.14	48.86	[illegible]	48.39
– Efficiency – Improvement vs. baseline (%)			2.6		2.8	4.9		5.8	5.1		[illegible]	5.2
Fares relative to 1973	1.000	0.995	1.056	0.957	0.956	0.920	0.954	0.895	0.912	0.931	0.918	0.904
Total flights/day	6615	7328	7258	8260	8067	8445	8932	8860	9164	[illegible]	[illegible]	[illegible]
Load Factor (%)	52.2	55.7	55.1	57.3	57.1	58.4	57.7	58.4	58.5	60.8	58.4	57.9
Average stage length (mi)	589	660	662	697	694	694	712	708	708	730	704	708
Average block time – (hrs) (baseline average stage length)	1.63	1.68	1.36	1.71	1.80	1.87	1.29	1.37	1.35	1.87	1.54	1.82
Fleet size – total	1382	1949	1532	1721	1754	1819	1992	2006	1993	2597	2671	2381
– B-747	69	113	99	207	218	263	263	307	394	590	688	695
– DC-10/L-1011	308	240	287	254	332	336	488	414	453	481	611	640
– DC-8/B-707	356	35	52	0	0	0	0	0	0	0	0	0
– B-727-200/200A	533	728	756	845	836	881	938	948	932	994	1004	996
– B-737-200/DC-9-10/30	345	388	429	368	434	358	885	289	883	1190	1183	10
– Turboprop	13	1	1	0	0	0	0	0	0	0	0	0

TABLE IX (cont'd)

AIRCRAFT RETROFIT/MODIFICATION OPTIONS
(RECAT 600 City-Pair Network)

	1980						2000					
	Baseline	Aero (In-Prod. Only) IIIa[1]	Proj. Retirements Aero IIIa[1]	Proj. Retirements Aero & Eng. IIIb[1]	Xc 75-80 Retirements Aero IIIa[1]	Xc 75-80 Retirements Aero & Eng. IIIb[1]	Baseline	Aero (In-Prod. Only) IIIa[1]	Proj. Retirements Aero IIIa[1]	Proj. Retirements Aero & Eng. IIIb[1]	Xc 75-80 Retirements Aero IIIa[1]	Xc 75-80 Retirements Aero & Eng. IIIb[1]
Enplaned pass. miles (10^9)	[illegible]	[illegible]	281.64	281.31	174.97	[illegible]	436.13	439.05	439.09	439.14	439.32	439.48
Fuel: Total (10^9 gals/yr)	[illegible]	[illegible]	9.858	9.823	9.737	9.730	[illegible]	15.421	15.337	15.329	15.252	15.200
Savings vs. Baseline (%)												
Actual - annual	—	5.7	6.6	[illegible]	7.6	7.7	—	[illegible]	6.5	6.6	7.0	7.3
- cumulative since 1973	—	3.8	3.5	3.9	[illegible]	3.8	—	4.9	5.0	5.3	4.9	5.6
Adjusted - annual	—	6.3	7.0	7.2	7.4	7.4	—	6.6	7.1	7.2	7.7	8.0
- cumulative since 1973	—	4.3	3.9	4.0	[illegible]	3.0	—	5.4	5.5	5.6	5.0	5.4
Efficiency: Pass-Mi/gal	26.12	[illegible]	28.60	28.84	28.73	28.87	26.54	28.47	28.63	28.67	28.80	28.91
Seat-Mi/gal	46.[illegible]	[illegible]	49.6	49.7	[illegible]	50.1	46.4	49.1	49.3	49.4	49.6	49.8
Fares vs. 1973	[illegible]	[illegible]	0.946	[illegible]	[illegible]	0.955	0.937	[illegible]	[illegible]	0.930	0.930	0.929
Total flights/day	8,659	8,71[illegible]	8,[illegible]	8,831	8,591	8,[illegible]	[illegible]	[illegible]	[illegible]	11276	11336	11206
Load factor (%)	57.7	57.8	57.7	57.7	57.5	57.3	[illegible]	[illegible]	58.0	58.1	58.1	58.1
Emissions (10^3 wtd. tons)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	93.793	93.787	[illegible]	93.981
Noise vs. 1973	1.069	[illegible]	[illegible]	[illegible]	1.044	[illegible]	[illegible]	1.070	1.207	1.210	1.203	1.281
Fleet size: Total	1,491	[illegible]	1,[illegible]	[illegible]	1,474	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2593	2555
B-747	353	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	811	802	774	783
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	721	719	761	760
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B-727-[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	956	971	971	975	[illegible]	966
B-707-[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
B-707-[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	107	111	113	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DC-9-[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Turboprop[2]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
New aircraft investment[3] (Since previous forecast ($10^9$$)	13.877	14.069	14.944	[illegible]	15.918	16.995	[illegible]	[illegible]	29.929	29.549	28.693	[illegible]
Cumulative present value ($10^9$$) (8% discount)	[illegible]	14.095	13.851	[illegible]	[illegible]	[illegible]	[illegible]	14.883	[illegible]	[illegible]	17.997	18.357

[1] fixed fleet size [2] includes cost of retrofitting existing aircraft

TABLE XI

NEW FAR-TERM AIRCRAFT OPTIONS
RECAT 600 CITY-PAIR NETWORK

	1973	1980	1985		1990					2000				
		Baseline	Baseline	Turboprop (VIa)	Baseline	Turboprop (VIa)	Turboprop (VIb)	Turbofan (VIc)	Turbofan & Turboprop (VId)	Baseline	Turboprop (VIa)	Turboprop (VIb)	Turbofan (VIc)	Turbofan & Turboprop (VId)
Enplaned Pass.-Miles (10^9)	107.50	168.83	224.14	223.42	280.45	281.15	281.36	285.20	284.[illegible]	436.13	436.31	436.44	447.95	447.05
Fuel: Total (10^9 gals)	5.808	6.656	8.440	8.165	10.536	9.955	10.193	9.649	9.620	16.400	15.386	15.417	12.168	12.168
Savings vs Baseline (%)														
Actual	-	-	-	3.3	-	5.5	3.3	8.4	8.7	-	6.2	6.0	25.8	25.8
Adjusted	-	-	-	2.9	-	5.7	3.6	10.0	9.9	-	6.2	6.1	27.8	27.6
Efficiency: Pass-mi/gal	18.51	25.37	26.56	27.36	26.62	28.24	27.60	29.56	29.55	26.59	28.36	28.31	36.81	36.74
Rent-mi/gal	36.15	45.53	46.32	47.78	46.17	48.75	47.70	50.95	51.05	45.86	48.82	48.74	63.38	63.27
Improvement vs Baseline	-	-	-	3.2	-	5.6	3.3	10.4	10.[illegible]	-	6.5	6.3	38.2	38.0
Fares Relative to 1973	1.000	0.995	0.957	0.958	0.959	0.947	0.947	0.934	0.935	0.937	0.935	0.935	0.897	0.899
Load Factor (%)	51.2	55.7	57.3	57.3	57.7	57.9	57.8	58.0	57.9	58.0	58.1	58.1	58.1	58.0
Flights/Day	6615	7328	8240	8239	8959	8945	9019	8990	8964	11,103	10,984	11,054	10,517	10,543
Average Capacity - Seats/Flight	136	172	192	193	209	211	204	212	214	249	256	255	275	273
Fleet Size: Total	1372	1549	1771	1767	1992	1978	1996	1996	1981	2551	2511	2524	2428	2430
B-747	65	113	227	214	353	351	356	244	244	840	868	869	253	256
DC-10/L1011	100	240	34[illegible]	306	455	334	357	324	365	651	389	380	314	397
B-737-200	247	619	845	765	955	773	361	849	849	956	601	626	546	620
B-737-200/DC-9-30	259	368	360	359	228	227	231	231	231	110	106	108	105	104
Other[1]	701	209	0	0	0	0	0	0	0	0	0	0	0	0
N85-200P	-	-	-	123	-	192	192	-	201	-	546	540	-	549
N85-200	-	-	-	-	-	-	-	965	-	-	-	-	695	-
N85-500	-	-	-	-	-	-	-	92	92	-	-	-	515	504
New Aircraft Investments ($10^9$$)														
Since Previous Forecast	12.749	7.932	7.836	8.171	13.877	14.385	14.414	14.803	14.673	30.256	31.375	31.362	32.021	31.831
Cumulative 1973 Present Value (8% Discount)	-	5.900	9.551	9.707	13.951	14.268	13.122	14.245	14.204	19.436	19.956	19.808	20.050	19.975

1 DC-8, DC-9-10, B-707, B-720, B-727-100, TV-880, Turboprops